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RADIO TELEPHONE MODULATION

BY

HUGH A. BROWN

AND

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BULLETIN NO. 148

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RADIO TELEPHONE MODULATION

I. Introduction

1. *Nature of Problem.*—The purpose of this bulletin is to present, and interpret if possible, the results of an experimental investigation of the intensity or degree of modulation obtained with representative types of radiophones now in use and also with some modifications of these types which have suggested themselves as the work progressed. No comparative data of a quantitative nature are available; indeed, practically no comprehensive qualitative comparisons have ever been published. Many radio engineers have discussed and described systems in which they are particularly interested, but in practically no case have they submitted oscillograms or other data to show the percentage of modulation actually obtained on the high frequency power output of the device. Some have shown criteria for 100 per cent modulation, assuming ideal conditions which they do not utilize in practice on account of high cost, excessive heating of modulators, etc. The authors understand that in some standard sets the maximum modulation obtained is actually about 60 per cent, a commendable attainment under the difficulties mentioned.

In the recent past, brief experiments have been made with different radiophone transmitters and short accounts of these have been published.* In these papers a few oscillograms of rectified antenna current are shown, but the conditions for best modulation and efficiency are not discussed at length. No dynamic characteristic performance curves are shown, although such curves are just as necessary to the understanding of the characteristic functioning of radio telephone transmitters as they are in the case of dynamos and motors. The practising radio engineer should be familiar with such curves in order to choose the apparatus best suited to his needs. Strange as it may seem, performance curves are entirely lacking in the publications on the subject of radiophone transmitters.

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*Radio Review, Vol. 2, pp. 409-419, Aug., 1921; also Jahrbuch der Drahtlose Telegraphie, Vol. 21, pp. 120-128.

2. *Acknowledgments.*—The authors wish to acknowledge the helpful criticisms and suggestions given by Professors E. B. PAINE, MORGAN BROOKS, J. T. TYKOCINER, and A. P. CARMAN of the University of Illinois.

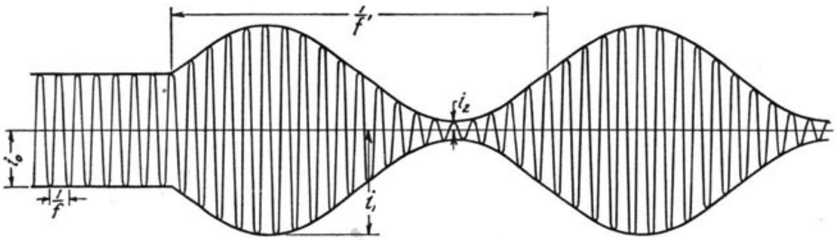

FIG. 1. A MODULATED WAVE

II. THE MODULATED WAVE

3. *Elementary Theory.*—Figure 1 shows a sine wave of normal frequency f, called the carrier frequency, modulated by a super-imposed voice frequency f'. The degree of modulation is determined by amplitudes at t_1 and at t_2, and the formula for per cent modulation is

$$100 \frac{i_0 - i_2}{i_0}$$

if modulation is "symmetrical." The equation for the modulated wave is

$$i = (I_0 + K\, I_0 \cos 2\,\pi f'\, t) \sin 2\,\pi ft\, *$$

For 100 per cent modulation the equation reduces to

$$i = (1 + \cos 2\,\pi f'\, t)\, I_0 \sin 2\,\pi ft \qquad K = I$$

Expanding, this expression becomes

$$i = I_0 \sin 2\,\pi ft + \frac{I_0}{2} \sin 2\,\pi\,(f + f')t + \frac{I_0}{2} \sin 2\,\pi\,(f - f')t$$

This is the well-known equation showing the existence of a so-called "carrier component" I_0 sin $2\pi\, ft$ and the two so-called "side band components;" the upper side band is denoted by $\frac{I_0}{2}$ sin 2π $(f + f')t$ and the lower side band by $\frac{I_0}{2}$ sin $2\,\pi(f - f')t$. Frequencies $f + f'$

*Heising, Proceedings I. R. E., Vol. IX, p. 305, Aug., 1921.

and $f - f'$ are the upper and lower side band frequencies respectively.* Speech may be transmitted even though the carrier component and one of the side band components be filtered out or suppressed in the transmitter under certain restrictions as discussed in the two papers referred to.

4. *Degree of Modulation Desired.*—Ideal Conditions: When the voice of the speaker modulates the high frequency power output the greatest transmission range will be obtained if this radiated power is varied 100 per cent when the speech sounds are strongest. The maximum degree of modulation should really not exceed 50 per cent or serious distortion of the voice transmission will result. It must be remembered also that during speech the intensity of sound varies greatly, perhaps from 100 per cent down to 5 or 10 per cent of this value, and that the per cent modulation in the ideal case must be in direct proportion.

The minimum value must, however, transmit audible signals. For best results an average voice tone should give approximately 50 per cent modulation with the extremes never exceeding 100 per cent, near which value distortion supervenes, nor falling below 10 per cent, which approaches inaudibility with weak receiving apparatus. The range of modulation demanded in the true transmission of music is much greater than for speech and the requirements of the transmitting equipment are accordingly more severe.

This wide range of modulation obtains in the various types of radiophone transmitters described in texts and in engineering papers. The typical oscillograph records, subsequently shown, illustrate percentage modulation obtained in certain types of radiophones with which the authors are familiar.

III. Method of Measuring Percentage Modulation

5. *Cathode Ray Oscillograph.*—The cathode ray oscillograph has been recommended for use in measuring high frequency potentials and currents. Methods of making such measurements are described and illustrated in publications of the manufacturers of the apparatus. The measurements are made by observing deflections of a cathode ray beam controlled by the current or potential under measurement.

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*For a more complete theoretical discussion see "Relations of Carrier and Side Bands," by R. V. L. Hartley, Proc. I. R. E., Feb., 1923.

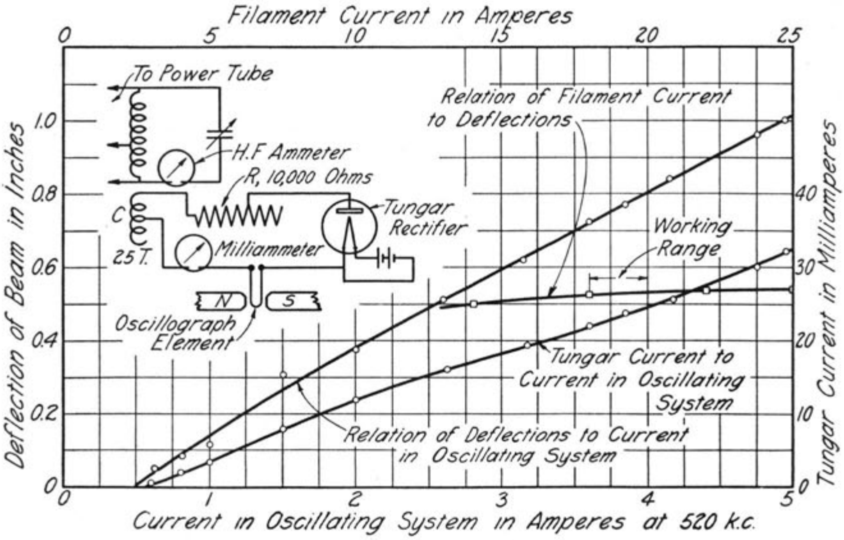

FIG. 2. CALIBRATION OF OSCILLOGRAPH WITH CURRENT THROUGH TUNGAR RECTIFIER

From the available data and descriptions it would seem that the use of the cathode ray oscillograph would be a simple, easily manipulated, and fairly accurate method of measuring percentage modulation. Experience, however, has shown the apparatus to have some extremely serious defects. It was not found possible to obtain consistent measurements, due to the fact that changes in the temperature of the incandescent filament in the device would not cause proportional effects on the deflection of the cathode ray beam for all amplitudes of deflection. The beam is focused on the screen by variation of filament temperature. To get a well-focused spot when the beam was motionless or when the amplitude of deflection was small, it was found necessary to operate the filament at a lower temperature than when the deflection was large. On this account errors were introduced in comparisons of maximum and minimum values of high-frequency currents represented by the deflections of the beam. For modulation up to about 25 per cent the method was satisfactory.

6. *Crystal Rectifier.*—An attempt was made to use various kinds of crystal detectors in series with a coil coupled to the high frequency

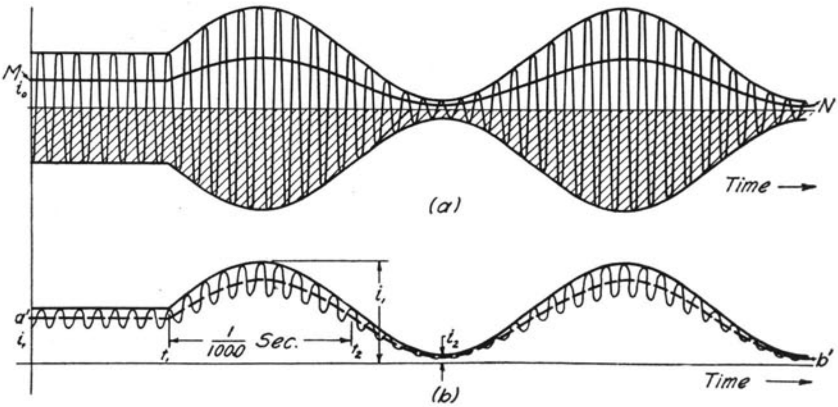

FIG. 3. RECTIFIED MODULATED HIGH FREQUENCY CURRENT

source and an element of a standard oscillograph, so that oscillograms of rectified high frequency current could be obtained. The most serious difficulty encountered was that 30 or 40 milliamperes are required to produce one-inch deflections of the oscillograph beam, and such a current burns the crystal contact very quickly and makes results unreliable. Rectifying crystals obey the "square law," i.e., the current is proportional to the square of the e.m.f., and therefore the results obtained are not in actual direct proportion.

7. *The Tungar Tube Rectifier.*—The crystal rectifier was replaced by a rectifier tube of the type used in the Tungar rectifier, and a calibration curve was obtained, connections being made as shown in Fig. 2. The effective value of the high frequency current was varied and readings of current and deflection of the beam in the rectified circuit were obtained. The curves of Fig. 2 show the characteristic of the rectifier tube current to be almost linear or proportional to the high frequency current through a wide range. One curve shows how the deflection varies with a change in filament current of from 14 to 25 amperes. In all subsequent work the filament current was maintained at from 18 to 20 amperes, the range indicated on the curve.

The variation in amplitude of the high frequency current i_0 in Fig. 3 could be as shown, assuming a sine wave of modulating e.m.f. The lower half of this wave is entirely cut off by the rectifying action of the Tungar tube. The shaded portion of the curve of Fig. 3a is removed and pulsating high frequency voice modulated currents will then tend to flow in the oscillograph element circuit. For voice modulation the oscillograph beam would have amplitudes proportional to the average value of the radio frequency pulsating currents, and may follow some such variation as line MN. If there is a constant ratio between the maximum value and the average value of the radio frequency pulsating currents these indicated amplitudes should give correct measurements of percentage modulation.* However, it is reasonable to suppose that the pulsations at radio frequencies are smoothed out somewhat by the inductance of the circuit so that actual conditions are as represented by curve b of Fig. 3. The deflections will then follow line $a'b'$ and the greater the inductance the more nearly will $a'b'$ approach the modulating envelope in form.

This feature was investigated further and some very interesting phenomena were observed. A constant current modulator was set up and arranged to modulate the output of a vacuum tube oscillator.† High frequency induced current from the oscillator was passed through the Tungar tube, an oscillograph element, a variable inductance (variometer), and a resistance of about 100 ohms in series. A pair of plates of a cathode ray oscillograph was connected across the resistance and when rectified radio frequency currents flowed through the resistance the cathode beam formed a line always on one side of the zero as expected. When the inductance was increased the amplitude of deflection of the cathode beam was reduced, but the beam moved further away from its original zero position. When the inductance was increased to 0.2 millihenry the beam became stationary but displaced from the zero, showing that the high frequency pulsations were apparently entirely smoothed out into a steady unidirectional current. Then when the output of the oscillator was modulated with voice frequency potentials or a 500-cycle e.m.f. the cathode beam was deflected in a manner similar to the oscillograph beam. Next the percentage modulation was measured from the oscillograph rectified current deflections for varying values of smoothing-out inductance and it was found that the measured value increased 10 per cent when the inductance was increased from 0.06 to 0.5 millihenry. Oscillogram "a" of Fig. 4 shows the effect of increasing the inductance from 0.06 to 0.1 millihenry, the percentage modulation indications in-

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*The formula for percentage modulation is derived on p. 30.

†This system is described in detail on p. 11.

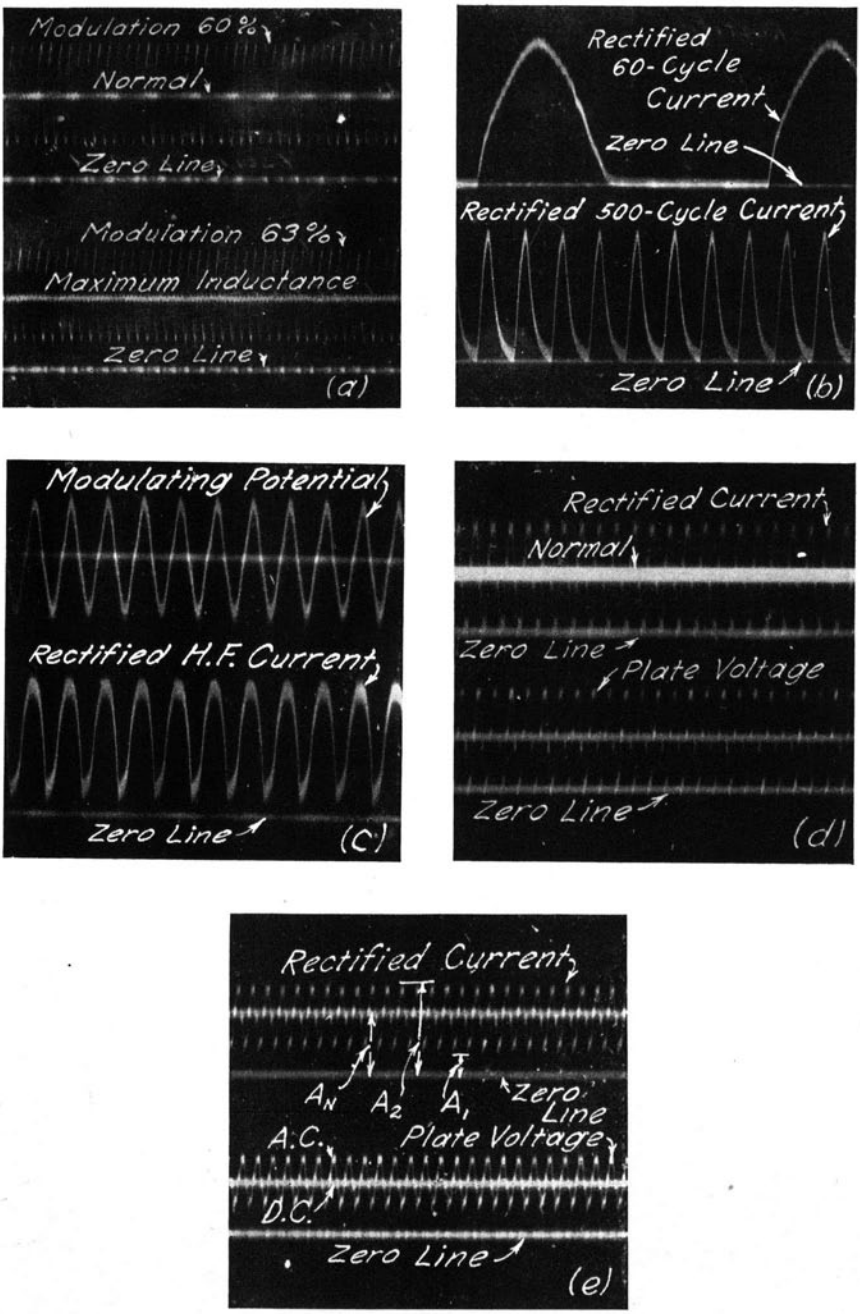

FIG. 4. TYPICAL OSCILLOGRAMS OF RECTIFIED CURRENTS

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creasing about 3 per cent. Oscillogram "b" of the same figure was taken to show results obtained when passing 60-cycle and 500-cycle alternating currents respectively through the Tungar tube and oscillograph. A lagging or smoothing-out tendency is noted even in the case of the 60-cycle wave and in the case of the 500-cycle wave it is sufficient to prevent the current from returning to zero during the negative half-wave. This would indicate a source of error in the Tungar rectifier and oscillograph method of measuring percentage modulation. To investigate the point briefly, a 500-cycle modulating potential was applied to the oscillator and this potential increased until a change in the wave shape was shown by the rectified current oscillogram. This indicated over-modulation which should show up as 100 per cent on the oscillogram, and this was almost the case. Then the modulating potential was lowered until the wave shape appeared the same as that of the modulating potential and an oscillogram taken. The results are shown in "c," Fig. 4. The degree of modulation calculated from the measurements on the narrow beam used for observation on the oscillograph screen was about 90 per cent; but the value from the oscillogram print appears to be only 85 per cent due to the very wide beam used.

The authors were not convinced that the rectifier tube gave accurate indications; hence, another line of attack was followed. A special 500-cycle power transformer, having a secondary voltage of 1000 or 2000 volts and a primary voltage of 125 volts, was obtained. A variable resistance was placed in the field of the 500-cycle generator used to excite the transformer, so that the voltage could be varied. The secondary of this transformer was connected in series with the plate circuit supply of a 50-watt power tube, its plate supply being 1000 volts direct current from a d-c. generator. In this way the 500-cycle voltage was superimposed on the direct-current supply voltage. The amplitudes of the two voltages were observed on the oscillograph screen and adjusted until they were equal. If the oscillator tube has a linear relation between plate voltage and output current, 100 per cent modulation of the latter should be obtained. The rectified current oscillogram was obtained for this condition and the result is shown in Fig. 4. The indicated modulation is a full 100 per cent, as shown by oscillogram "d" of the figure. Then the amplitude of the 500-cycle superimposed e.m.f. was reduced and a proportional decrease in modulation resulted. The results are shown in oscillogram "e" of the figure. The results of this test are convincing proof that the rectified current oscillogram is a fairly accurate means of measuring percentage modulation.

IV. Simple Methods of Low Power Modulation

8. *Microphone in Antenna Circuit.*—If the resistance in the antenna of a radiating system or in the output circuit of an oscillating power tube be varied at voice frequencies a modulated wave will result. Many years ago this method was experimented with a great deal* and multiple microphones were constructed which could carry 5 or 6 amperes satisfactorily. The modulation was unsatisfactory, however, and the method was later abandoned. No data were obtained on this method in connection with this investigation.

9. *Direct Grid Modulation.*—Modulation by superimposing voice frequency potentials upon the grid of an oscillating power tube is known as "Logwood's System." Connections were made as shown in Fig. 5, and modulation was obtained by emitting an "ah" sound into the microphone *m* and making adjustments while observing results on the oscillograph screen. It was thought best to use the microphone and speech amplifier for certain tests rather than to provide a measured audio-frequency e.m.f., as actual operating conditions and limitations were obtained. The quality of modulation was always observed by listening in with a tuned receiving set, placed so that it was not operated by induction potentials but had to be tuned to the radiation field. This method of test was used in all subsequent work, with a few exceptions, because the authors were desirous of obtaining maximum possible modulation with a microphone and actual speech. The data secured indicated that this method of modulation was very ineffective, only about 5 per cent modulation being obtained. An oscillating vacuum tube seems to be insensitive to grid modulation. There are probably two reasons for this: First, the grid potential varies through a wide range, and has a high maximum value, and the superimposed speech potentials are relatively low; however, the potential across the transformer secondary should have been between 500 and 1000 volts. Secondly, it is necessary to shunt the secondary of the transformer with a condenser of about 0.002 m.f. capacity, in order to by-pass radio-frequency grid currents. This partially short circuits the audio-frequency potentials. The tube *O*, Fig. 5, was a 5-watt tube, and the output was about 4 watts. Large power tubes are even more insensitive to grid modulation. Modulation might be improved somewhat by using a higher power speech amplifier, but probably not to a great degree. If

*See Goldsmith, "Radio Telephony."

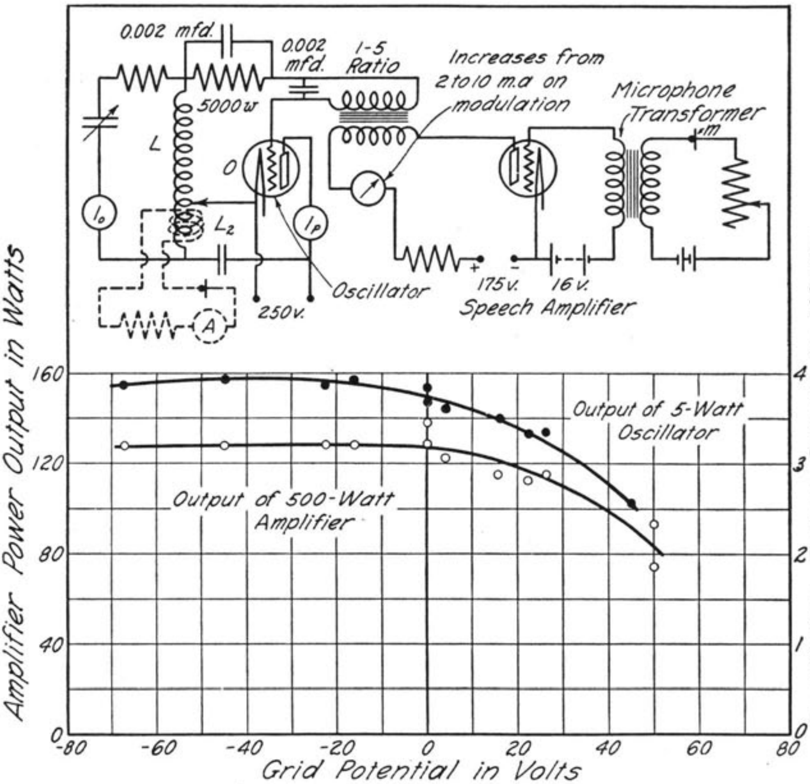

FIG. 5. CHARACTERISTICS OF DIRECT GRID MODULATION

the grid potential exceeds a certain negative limit the plate resistance becomes almost infinite and the tube stops oscillating. The variation of the output of a 5-watt tube with superimposed grid potential is shown in Fig. 5. It is very evident from this curve that the possible modulation is not only very weak, but also inaccurate, giving rise to distortion, because the relation of output current to grid potential is not linear in the region where the former does vary somewhat. A 500-watt power amplifier was excited by means of the 5-watt system of Fig. 5, and the resulting variation of the output is also shown in Fig. 5. This illustrates the inefficiency of such a system.

10. *Absorption Loop Method.*—Referring again to Fig. 5, if a coil L_2, consisting of 3 or 4 turns, is placed concentric with L and coupled

as closely as possible, and if a microphone, variable resistance, and thermo-milliammeter be placed in circuit with L_2, the power absorbed in this circuit will vary in accordance with the sound waves striking the microphone; and the radiated field from the open radiator portion of the oscillator will vary similarly but in opposite phase relation to that in the absorbing circuit. Data were secured, using 12 turns in L_2 and from 0.20 to 0.25 amperes in the microphone. Modulation up to 38 per cent was obtained. A serious defect, at once evident, was the large falling off in power and radiation. Fewer turns in L_2 resulted in less microphone current, less falling off in amplitudes, and lower percentage modulation. An increased number of turns in L_2 gave the opposite effects. This system could be used as the master oscillator supplying a power amplifier if the falling off in radiation could be prevented.

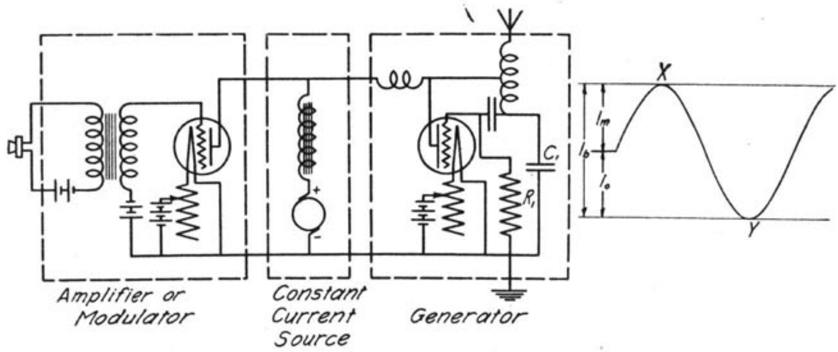

FIG. 6. THE CONSTANT CURRENT SYSTEM

V. CONSTANT CURRENT SYSTEM

11. *General Elementary Theory.*—The constant current system of modulation, or "Heising System," is in general use at the present time for powers ranging from 5 watts to 10 k. w. In the original system, as described by Heising,* equal numbers of modulator and oscillator tubes are shown. Figure 6 is a diagram of the apparatus reproduced from the paper to which reference has just been made. In the same figure are shown curves representing the division of oscillator and modulator plate currents as also shown in this paper. When a sine wave is used for modulating, the plate currents vary between twice normal and zero value, the average value of the pulsating plate currents remaining the

*Proceedings I. R. E., Vol. IX, No. 5, Aug., 1921.

same. The plate voltage on the oscillator tube, due to the effect of the constant current choke, was shown to vary between twice normal and zero values, resulting in 100 per cent modulation; and Heising shows that the power output will increase 50 per cent, or the antenna current increases in proportion to $\sqrt{1.5}$. In actual practice it has been found that the modulator plate current cannot be maintained equal to the oscillator plate current. Generally one-half of the power supplied to the oscillators is usefully employed in the oscillating circuit, and the remaining half heats the plate; but all of the power delivered to the modulator plates heats them when there is no modulation. To prevent overheating, twice as many modulators as oscillators would be required. This difficulty has been surmounted by maintaining a high negative grid bias on the modulators so that the plate current is nearly zero normally and builds up to an average value equal to that of the oscillators when modulation obtains. It is believed that for good modulation it is necessary to use more modulators than oscillators. Furthermore, the potential across the choke could not change if its inductance were so high that $\frac{di}{dt} = 0$. In order that the power output of the oscillators may vary with audio-frequency variations of modulator plate resistance, the voltage on the oscillator plates must vary because the relation between output of a power tube and plate voltage supply is nearly linear. This means that the plate voltage on the oscillators must at any instant be

$$e_p = E_{p_0} + L\frac{di}{dt} \text{ (where } E_{p_0} \text{ is the supply voltage)}$$

and there is a value of L for each modulation frequency which will give a maximum value of $L\,\frac{di}{dt}$. In practice this choke is usually of the order of 20 to 50 henries for medium power. The correct value for practical results was investigated and will be discussed.

12. *Modulation of Low and Medium Power.*—Figure 7 shows one 5-watt oscillator and two 5-watt modulators, the output circuit including an inductance, capacity, and resistance of known value. Modulation was first obtained with a microphone transformer and a microphone circuit only, and later with the aid of a one-stage speech amplifier as shown.

Data obtained in these two cases indicated that even in the case of 5-watts output a speech amplifier tube is desirable if deep modulation

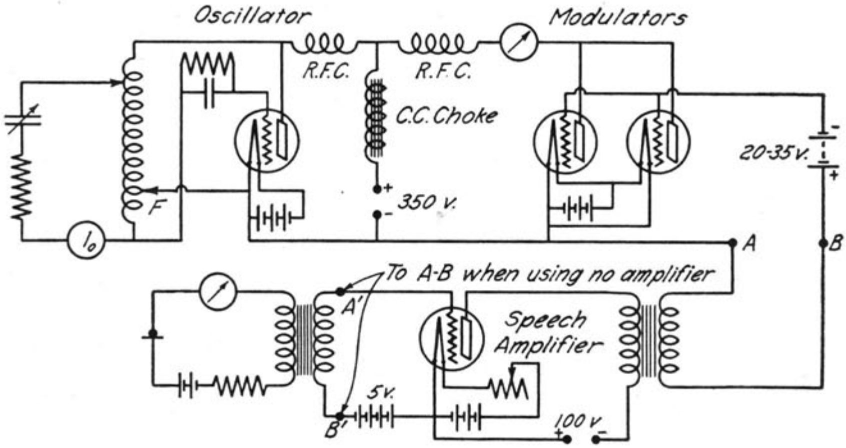

FIG. 7. CONNECTIONS FOR CONSTANT CURRENT MODULATION

is desired. The modulator plate current was found to increase upon modulation, the increase being greater with the use of the amplifier than where only the microphone and transformer were used. A general rule can be made that the greater the increase in modulator plate current, the greater the degree of modulation secured.

A difficulty often encountered in practice is that the output of the system falls off when modulation begins. This difficulty is encountered with nearly all the systems in use. Fortunately, it can be avoided in the constant current system by proper adjustments. It is due to several causes: (a) low filament temperature in oscillator, (b) wrong excitation of oscillator grid, (c) too much load resistance in oscillator output circuit, and (d) over modulation of oscillator. The excitation of the grid in the case of the Hartley circuit (used in nearly all of the subsequent tests) should be carefully adjusted by varying the position of the filament tap on the oscillator inductance *F*, Fig. 7. This is very critical in the case of high voltage tubes such as the 250-watt, 2000-volt tungsten filament tube. With all adjustments made to secure the best modulation it was found that 75 per cent modulation could be obtained. This was the maximum obtainable, using a Western Electric No. 284-W microphone carrying 0.1 ampere current and emitting the vowel sound "ah" very close to the mouthpiece, and varying the pitch until the best modulation showed on the oscillograph screen. When it is remembered that modulation exceeding 100 per cent would cause prohibitive distortion it is probable that the value obtained, or 75 per cent, is the maximum

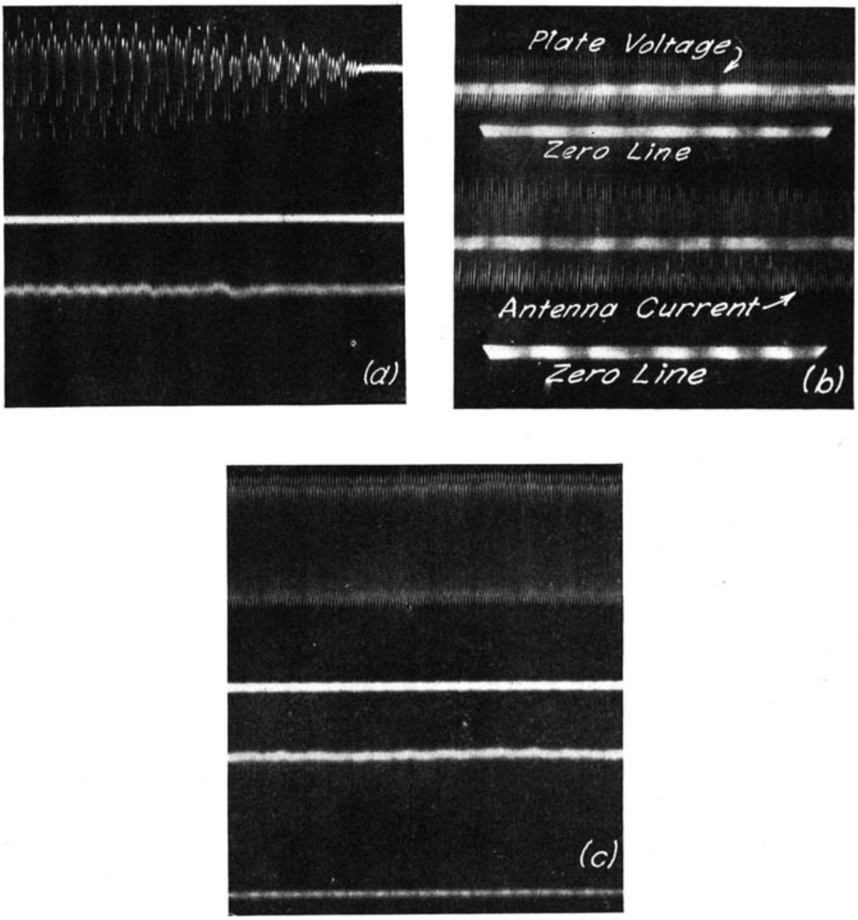

FIG. 8. OSCILLOGRAMS OF PLATE VOLTAGE DURING MODULATION

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allowable when the tone is steady. Modulation during impacts on the microphone which are liable to occur from certain types of articulation or music, should be limited to a maximum of 75 per cent.

A higher power system consisting of two 250-watt oscillators in parallel, modulated by three 250-watt modulators in parallel, was studied. The normal output of the system was 450 watts. The modulators were controlled by a 3-stage power amplifier, the last stage being a 50-watt oxide-coated filament tube with 500 volts on the plate. The constant current choke was 20 henries. Modulation up to about 45 per cent was secured under the same conditions as described for the low power system. It was found that while a single stage amplifier was sufficient in the case of the 5-watt system to produce 75 per cent modulation, three stages and much more power were needed in the case of the 500-watt system to produce 45 per cent modulation. It is entirely possible to produce as good modulation with the higher power systems as with the lower but the difficulties and expenses of power amplification of speech increase much more rapidly in proportion to the results obtained.

13. *Oscillator Characteristics.*—The oscillograms shown in Fig. 8 are representative of those obtained in the study of the various systems. Part "b" shows simultaneous variation of the plate voltage of the oscillator tubes and the rectified output or antenna current. This part shows the percentage variations of the plate voltage and the rectified output current to be about equal. In part "a," the upper curve shows the variation of the plate voltage of the oscillator tubes under modulation by a low pitched "ah." The lower curve of part "a" is a simultaneous record of the voltage supply back of the constant current choke of 20 henries, (see Fig. 7). Very little fluctuation is noted. In oscillogram "c" a high pitched whistle of about 1025 cycles was given, and there was no noticeable fluctuation of the supply voltage. Modulation is evidently quite effective in the constant current system, even when modified to its practical form. In obtaining the oscillograms (Fig. 8 a, b, c) the modulator plate current was normally held at 50 milliamperes and increased to 350 milliamperes (average value on the d-c. milliammeter) during modulation.

In the constant current system the plate voltage during modulation is expected to fluctuate at voice frequencies between zero and twice the normal value if the modulation is 100 per cent, and for other values in proportion. In order to accomplish this the operating charac-

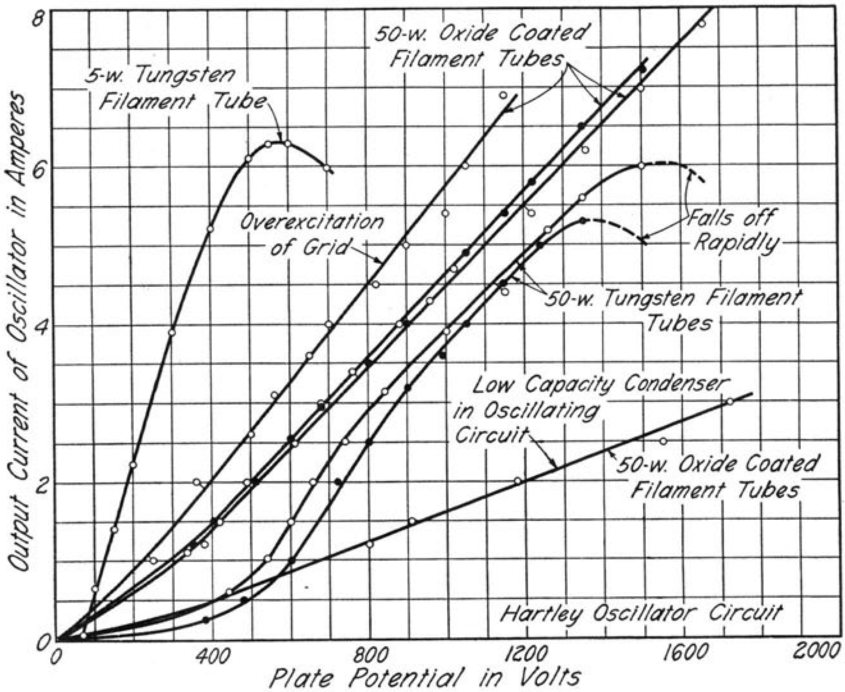


FIG. 9. PERFORMANCE CHARACTERISTICS OF OSCILLATOR TUBES

teristic of the oscillator must have a linear relation between zero and twice rated plate voltage. Figure 9 shows curves obtained with several 50-watt tubes. The oxide-coated filament tubes showed better characteristics than the tungsten filament tubes. The tendency of the latter to fall off in output at high plate voltages is probably due to excessive heating of the plates. They may possibly give desired results momentarily, but this could only be shown by dynamic characteristic curves. Investigation showed that abnormal conditions such as over-excitation of the grid, or too small a condenser in the oscillatory circuit, affect the shape of the characteristic and result in inefficiency or production of harmonics. When using tungsten filament tubes, distortion is likely to result from strong modulation due to the curving of the characteristic. Inspection of the curves indicates that such danger is obviated if the modulation does not exceed 50 or 60 per cent.

14. *The Constant Current Choke.*—The proper value of inductance for the constant current choke in the plate voltage supply lead has been

a point of much discussion. Various technical articles have been written on construction of radiophones in which the values of this choke are variously given as from 1.5 to 5 henries. The practice in some broadcasting stations is to use as much as 40 henries. To obtain some data on the variation of percentage modulation with inductance in the constant current choke an a-c. modulating potential of variable frequency

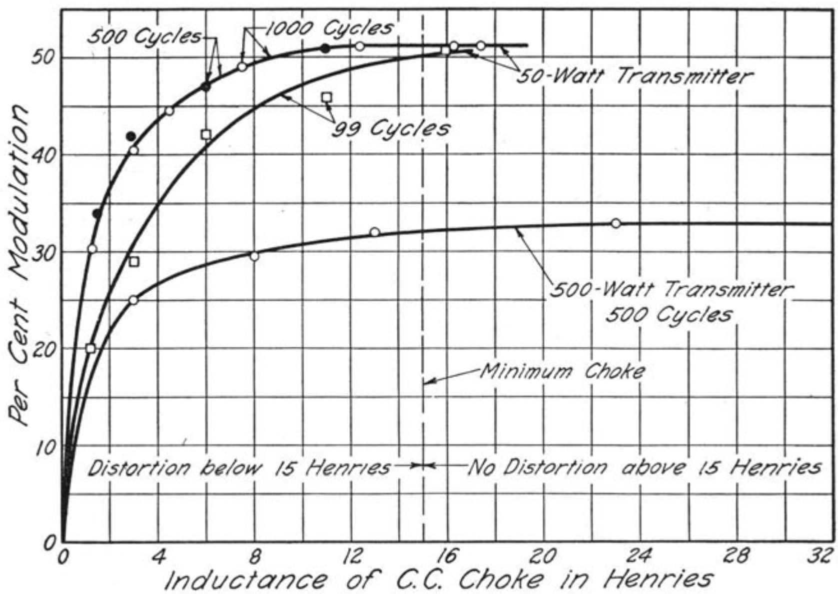


FIG. 10. RELATION OF PERCENTAGE MODULATION TO INDUCTANCE OF CONSTANT CURRENT CHOKE

was applied to the grids of the modulator tubes and percentage modulation measured for various values of inductance of the choke. The results are shown in Fig. 10 and are interesting, because even for low frequencies (99 cycles) of the modulating potential no increase of modulation occurs above 15 henries. The results on the 500-watt and 50-watt transmitters tested were alike. Below 15 henries some distortion may result; the curves indicate that 6 or 8 henries may be used without causing any more serious distortion than is caused by other limiting factors such as oscillator characteristics, amplifiers, receiving equipment, etc.

15. *Modulator Tube Requirements.*—It was previously stated that

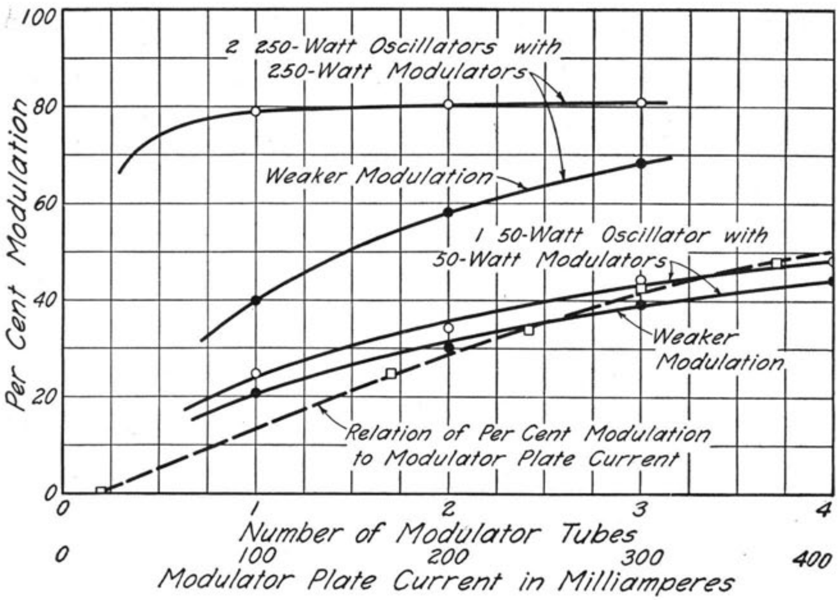


FIG. 11. RELATION OF PERCENTAGE MODULATION TO NUMBER OF MODULATOR TUBES

the practice has been to use about three modulators for every two oscillators. An equal number of each was proposed by Heising, but in practice it has been found that deep modulation is made quite difficult with the usual low modulator plate currents, and the addition of extra modulator tubes is beneficial. The number of modulator tubes was varied on 50- and 500-watt transmitters and readings of percentage modulation were taken. The results are shown in Fig. 11. When using two 250-watt oscillators (500 watts total), increasing the number of modulator tubes from two to three showed a gain of 10 to 15 per cent; increasing from three to four showed a further gain of about 5 per cent. For the one 50-watt oscillator the gain was twice as great. Where over-modulation occurred the results were of no value. The curves show that the number of modulators should be twice the number of oscillators for efficient modulation.

16. *Indications of Percentage Modulation.*—These observed results lead to the question as to what could be taken as an indication of percentage modulation in a constant current modulated transmitter. Figure 12 shows the results of the variation of measured modulation with the modulating 500-cycle potential. From the indicated upper

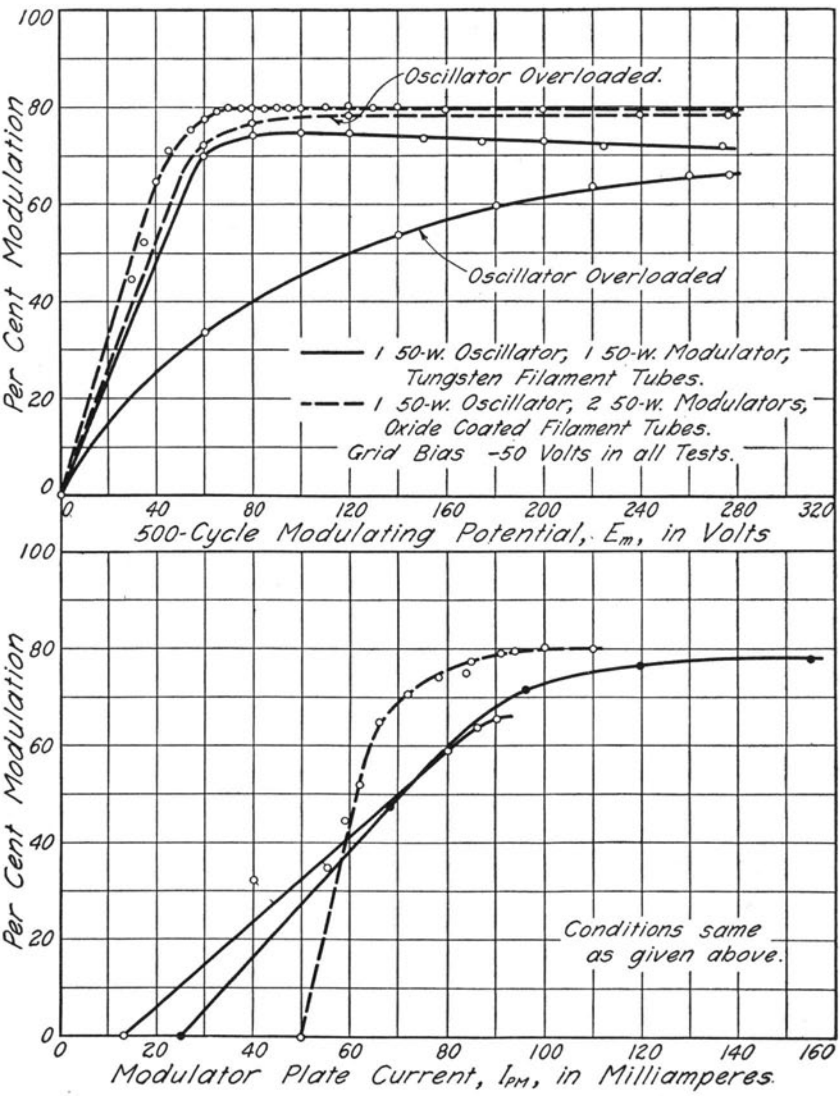


FIG. 12. RELATION OF PERCENTAGE MODULATION TO MODULATING POTENTIAL

limit of 80 per cent it must be concluded that either it is difficult to modulate more than 80 per cent when using high voltage tubes, or the Tungar tube rectifier and standard oscillograph cannot be relied upon to indicate accurately high percentage of modulation. From the experimental work it would seem that high voltage tubes present an inherent difficulty in approaching 100 per cent modulation as compared with low voltage 5-watt tubes with which records of 90 and 92 per cent modulation were readily obtained.

The relation between modulator plate current and percentage modulation is nearly linear for values up to 75 per cent. I_{PM} is the average value of the pulsating modulator plate current. The increase of this quantity during modulation is a fair indication of percentage modulation, and if the percentage modulation is known for a certain reading of the d-c. modulator plate current ammeter, with a specified unmodulated value, grid bias potential, and filament voltage, other values of percentage modulation may be calculated by direct proportion. In the tests represented by Fig. 12 maximum modulation was obtained when the direct-current meter readings of the oscillator and modulator plate currents were equal in value, the percentage modulation being 80 to 90. However, in the case of the 500-watt transmitter only 50 to 60 per cent modulation is indicated when the two plate current readings are equal. This also supports the view that deep modulation becomes very difficult with high voltage oscillators. The theoretical supposition that equal oscillator and modulator plate currents indicate 100 per cent modulation must surely be erroneous for high voltage high power tubes. Theoretically the indication of the ammeter in the oscillator circuit will be in the proportion $\sqrt{1.5}$ if the modulation is 100 per cent. This does not hold for tubes at overload, lowered filament temperatures, over excitation of the grid, and many other faulty adjustments, some of which will often cause the radiation to fall off slightly when modulation occurs.

VI. The Modulating Amplifier System

17. *Continuous Master Oscillator Type.*—This system was used in the experimental circuit at Arlington in 1915 when the radiophone was heard in Paris and Honolulu.* The circuit used in the present investigation was of course much simpler than the one referred to, and is shown in Fig. 13. The master oscillator, speech amplifier, and power amplifiers are indicated. Excitation of the last amplifier is most easily obtained by connecting its grid circuit in series with a part of the output inductance of the first amplifier circuit as shown. The output modulation varies with this excitation, which in turn is varied by the turns in either L_2 or L_3 by means of taps. The power output also depends upon the excitation. The circuit was adjusted to give best results. The degree

*Proc. I. R. E., Vol. IX, No. 4, Aug., 1921.

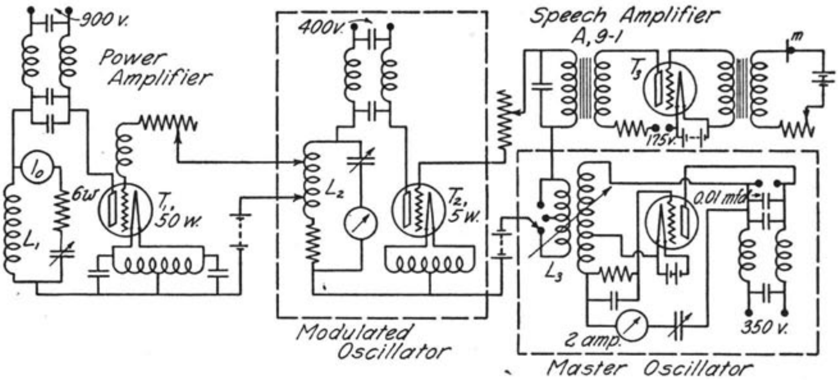


FIG. 13. POWER AMPLIFIER WITH MASTER OSCILLATOR

of modulation was observed with the oscillograph and did not exceed 40 per cent for 14 turns in L_2. By using 12 turns the modulation was reduced to 30 per cent. The output of the 50-watt power amplifier is not sufficient to excite effectively a 250-watt power amplifier tube; hence, two or more 50-watt tubes in parallel should be used. Data were not taken with a 250-watt tube, as an additional plate voltage supply, which was found necessary in the Arlington Experimental Circuit, was not then available.

18. *Precautions and Limitations.*—The following precautions are important:

(*a*) Care must be taken to excite T_2, Fig. 13, by inductive coupling to prevent high frequency induction in the master oscillator tube, resulting in insensitiveness and distortion.

(*b*) Shielding, indicated by the dotted lines, was found necessary to prevent feed-back action.

(*c*) The capacity of the condenser across A must be large enough to by-pass radio frequencies and yet not short circuit the audio-frequency voltages superimposed on the grid of the master oscillator. A capacity of 0.01 m.f. was found to be too large; 0.002 m.f. was used, but weakened both output of master oscillator and modulation somewhat.

(*d*) L_2 may be either inductively or conductively coupled, but could not exceed 14 turns when conductively coupled without making the power amplifier tube T_1 oscillate and hence become insensitive to modulation.

One of the serious limitations in the modulating amplifier system is its complexity. Much care must be used in tuning properly the high frequency oscillating circuits. These circuits should include rather large resistance to prevent distortion due to persistance of a high amplitude after the exciting potential has been modulated down to a low value. But high resistance in these circuits cuts down the current and weakens the excitation of subsequent amplifiers. Obtaining sufficient exciting potential on the grids of the power amplifiers presents other difficulties. When the frequency is 500 kilocycles or higher, intervalve transformers having a step-up ratio cannot be used as the tubes are apt to oscillate when the grid circuit is even approximately in tune with its output circuit. In the circuit experimented with, excitation potential was obtained by utilizing the $I_0 Z$ drop across L_2, Fig. 13. If the turns between the taps exceed 14, the tube T_1 begins to oscillate. Putting added resistance of several hundred ohms in the grid circuit usually prevents oscillation, but cuts down the excitation and output. Weak modulation also results unless the carrier component and one side band is filtered out, and the remaining side band amplified. To avoid poor modulation and distortion and to obtain efficiency in transmission seems to require an unduly large investment. Oscillograph observation shows that the radiation or output current falls off 25 per cent when modulation obtains. This serious defect can be only partially eliminated by great care in adjustments. Reduction of grid potential helps materially. The best degree of modulation obtainable on a sustained "ah" sound at the microphone was 40 per cent.

This test was made with one 50-watt power amplifier tube. When two 50-watt tubes in parallel were used the degree of modulation decreased 50 per cent. Reducing the power output from 25 to 15 watts improves the degree of modulation. However, the results obtained in the tests were not encouraging and show that for a fairly low power system, up to 100 watts at least, the method of Fig. 13 is not to be compared with the constant current system for efficiency, simplicity, degree of modulation, and good speech quality.

19. *Constant Current Modulated 5-Watt Master Oscillator.*—Much better results are obtained if the master oscillator possesses constant current modulation. To show this a 5-watt master oscillator was modulated with two 5-watt modulators, and a speech amplifier so that the degree of modulation of its output was as great as for the low power constant current system. This was used to excite two 50-watt tubes in

parallel whose unmodulated output was 70 watts. During modulation the output power fell off 30 per cent, but from 45 to 50 per cent modulation was easily obtained with the "ah" sound. It should be mentioned that the per cent modulation of the power amplifier output is 30 per cent less than the degree of modulation obtainable in the low power master oscillator itself. This constitutes another difficulty, and is due to the tendency of power amplifier tubes to persist in oscillation while being excited, making them partially insensitive to modulation unless the master oscillator has a greater output capacity as will be shown. Another common result is distortion, often rendering speech unintelligible. A simple remedy is found in reducing the excitation of the grid circuit, but this results in reduced output.

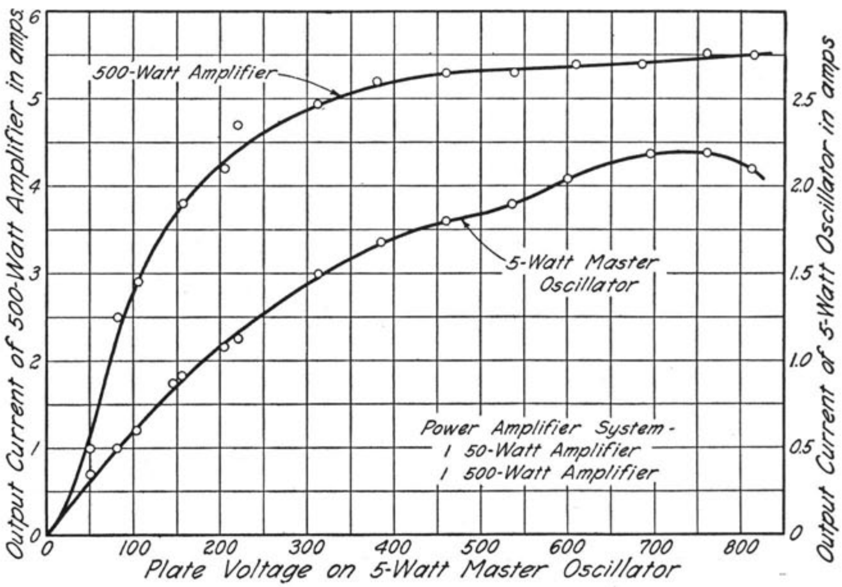


FIG. 14. PERFORMANCE CURVES FOR POWER AMPLIFIER SYSTEM

The same set-up was used to excite two 250-watt power amplifier tubes using one 50-watt tube instead of two in the intermediate step. The modulation observed was about 30 per cent and the efficiency less than 20 per cent during modulation. Figure 14 shows the relation between the plate voltage supply and the current in the output circuits of the 5-watt master oscillator and of the 500-watt amplifier. The normal plate voltage for the 5-watt tube was 350 volts but the impressed plate potential was carried up to more than twice normal, assuming that the modulator tubes connected to the 5-watt oscillator would cause a variation in the voltage of nearly 100 per cent. It will be noticed that the relation is not linear, and approximates the linear relation only between zero and normal, 350 volts. These curves were typical of several tests made and indicate that distortion is liable to result when the constant current modulation of the 5-watt oscillator is very strong. Care was taken in this test to see that neither of the amplifiers had a tendency to oscillate when not excited.

20. *Constant Current 50-Watt Master Oscillator.*—It was soon evident that a 5-watt power tube does not have sufficient output to excite effectively a 50-watt tube, and since there is practically no saving in

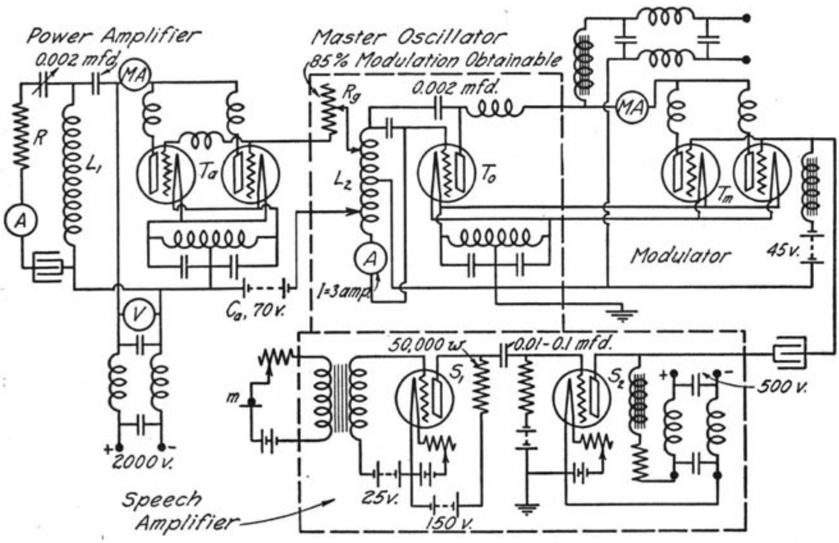


FIG. 15. CONNECTIONS FOR COMPLETE POWER AMPLIFIER SYSTEM

providing the 5-watt constant current modulating system when the extra plate voltage supply is considered, a 50-watt tube master oscillator modulated with two 50-watt modulators and a two-stage speech amplifier is justifiable, and was tested. The output was used to excite a 500-watt amplifier. The complete circuit diagram of the laboratory set tested is shown in Fig. 15. The 50-watt master oscillator and its output circuit were placed in a sheet-iron box to confine inductive activity and to avoid causing the amplifier tubes to oscillate when not excited. The speech amplifier was also shielded by a sheet-iron box and contained one 50-watt and one 5-watt speech amplifier tube as shown. With the grid bias potential set at negative 60 volts, oscillograph observations were made when modulating with the sustained "ah" sound. The degrees of modulation were 70 per cent for the master oscillator tube and 65 per cent for the power amplifier output. The output current and power of the master oscillator increased slightly upon modulating, but the output current of the power amplifier decreased 20 per cent and the power decreased from 400 to 250 watts when modulation began. The quality of speech reception on a laboratory receiver was excellent.

The following precautions must be observed in making adjustments: The grid circuit of the tubes T_a in Fig. 15 must remain untuned to the radio frequency, as has been previously mentioned. It was found that L_2 must be kept below 9 turns to prevent oscillation for a frequency of 600 kilocycles. Care must also be taken to have the current in L_2 rise approximately 15 per cent during modulation to maintain output unimpaired. R_g should be varied for best results. When tubes T_a are cut off, the ammeter reading in their output circuit should drop to zero; and if the master oscillator filament current is cut off, both high frequency ammeters should read zero. This shows that T_a does not persist in oscillation.

21. *Variation of Grid Potential.*—The previously discussed data and oscillograph observations were obtained under so-called "proper amplifier" conditions,* that is, the grid bias potential of the power amplifier tube was maintained sufficiently negative to make the plate current fairly low when the tube was not excited. It has been claimed that if the grid bias potential is held at a high negative value back of the zero plate current point, the power amplifier will give higher efficiencies.† The grid bias battery was removed and entirely different results were obtained with the set up of Fig. 15. The degree of modulation obtained was about 75 per cent and the record was similar to the best constant current oscillograms (see Fig. 4). The reading of the output high frequency current was 6.8 amperes and the power about 370 watts ($6.8^2 \times 8$). When modulation began on vowel sound "ah," the output current increased to 7.1 amperes, 403 watts. The normal input to the plate circuit, read on the d-c. meters, was 0.35 amperes $\times$ 1800 volts = 630 watts, and increased to $0.50 \times 1800 = 900$ watts. Taking the efficiencies as output divided by input, the efficiency was 58.8 ($\frac{370}{630}$) per cent normal and 44.8 per cent during modulation. The quality of speech reception was highly satisfactory. The experiment was repeated using one 50-watt

*Proc. I. R. E., Vol. IX, No. 4.

†Heising, Proc. I. R. E., Vol. IX, No. 7.

power amplifier excited by a 5-watt constant current modulated master oscillator. The grid bias was made 20 volts positive and the oscillograph showed symmetrical modulation. For the 20 volts positive grid the output was 50 watts during modulation with an input of $0.13 \times 850 = 110$ watts. The modulation, obtained from observation of the oscillograph beam, was a little less than 40 per cent in this case. Reducing the grid bias to -20 volts caused the output to fall off badly, as former tests showed. This was due to the inability of the 5-watt tube to excite the amplifier fully. The quality of modulation was checked and found to be very good. The claim has been made that the efficiency of a proper amplifier is never more than 25 per cent;* but here are actual cases, however, where about twice that value was obtained, taking efficiency as the ratio between the average power output $= I_0{}^2 R_0$ and the average plate input or d-c. plate voltage times the reading of the d-c. milliammeter in the plate voltage supply circuit. This may not be the true "plate circuit efficiency" of the tube as some have defined it, but it certainly is a good criterion by which to judge the performance and heating of the plate.

The interesting and satisfactory results obtained by reducing the grid bias potential made it desirable to investigate quantitatively the effect of variable grid bias upon the output, efficiency, and per cent modulation of a power amplifier excited by modulated and unmodulated high frequency currents. Using the weakly excited system of Fig. 13, which gives a rather poor output, the grid bias potential of the 500-watt power amplifier was varied from -135 volts to $+4.0$ volts and readings were taken of input and output of the power amplifiers. The input and output of the 50-watt amplifier did not change greatly, but that of the 500-watt amplifier varied considerably. Figure 16 shows how the output varies with the grid bias potential. The curves seem to indicate the best results at about -13 volts grid bias for heavily loaded tubes. For reduced load, however, increased negative grid bias potentials give the best results, see Fig. 16. From the curves it will be noted that the best efficiency and highest output do not occur at the same grid bias potential. The best operating value may be taken at either value depending on whether it is desired to force the tubes or not. The load was varied by varying the resistance in the output circuit. No modulation data were taken for this set up.

Connections were again made as in Fig. 15, a 500-watt amplifier

*Heising, Proc. I. R. E., Vol. IX, No. 4. See Appendix of Paper.

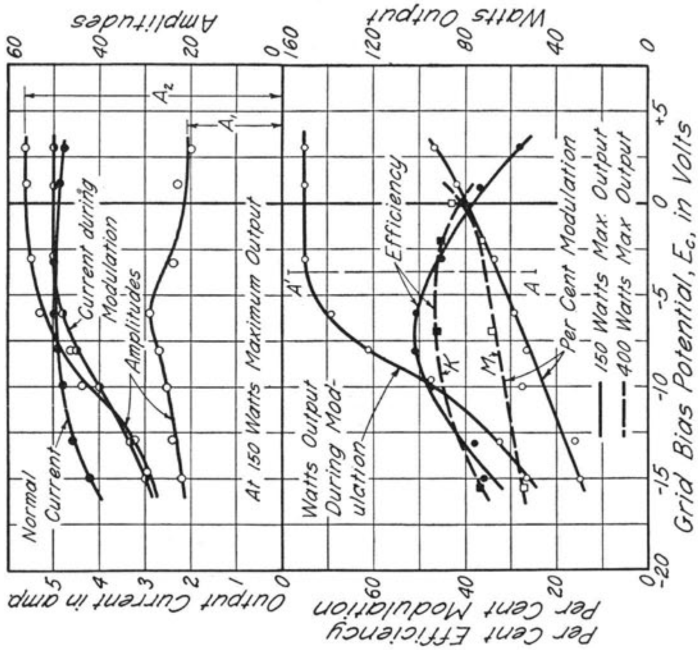


FIG. 17. EFFICIENCY AND MODULATION CHARACTERISTICS OF POWER AMPLIFIER SYSTEMS

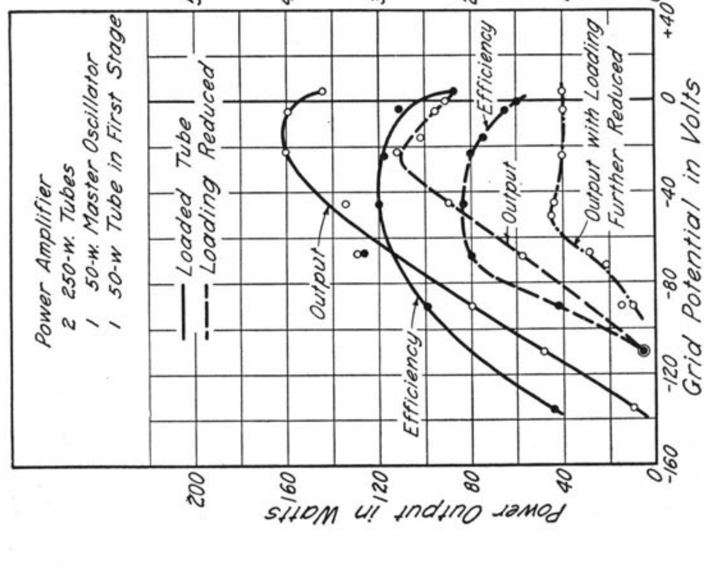


FIG. 16. RELATION OF TUBE EFFICIENCY TO GRID VOLTAGE IN POWER AMPLIFIER SYSTEMS

excited by a 50-watt constant current master oscillator being used. A dynamotor and high resistance potentiometer were introduced into the grid circuit so that the grid bias C_A could be varied between -100 and $+100$ volts. The grid potential was varied and modulation observed on the oscillograph screen while modulating as strongly as possible with vowel sound "ah" on the microphone. The unmodulated amplitude A_N, low and high amplitudes during modulation A_1 and A_2, and current and voltage readings were recorded. The results are shown in Fig. 17. The percentage modulation was determined by dividing the difference between the mean and minimum amplitudes by the mean between the maximum and minimum amplitudes or deflections of the oscillograph beam. Since the mean amplitude is

$$\frac{A_1 + A_2}{2}$$

where the minimum is A_1 and the maximum is A_2

then
$$M = \left(\frac{A_1 + A_2}{2} - A_1\right)\frac{1}{\frac{A_1 + A_2}{2}}\,100$$

$$= \frac{A_2 - A_1}{A_1 + A_2}\,100 \tag{1}$$

where M is the percentage modulation.

The unmodulated amplitude is A_n and some writers take

$$M = \frac{A_n - A_2}{A_n}\,100 \tag{2}$$

but if the power falls off and is lower during modulation this latter formula gives results greater than those actually obtained. If the amplitudes are equal above and below A_n (1) and (2) give the same result. Figure 17 was plotted from data obtained on the power amplifier excited by the 50-watt constant current modulated master oscillator, as previously described, and shows how the modulation changes with grid bias on the high power amplifier. As the negative grid bias decreases the per cent modulation increases and the output increases up to a limit, but the efficiency soon falls. In the figure it will be noted that for -16 volts the modulation is low and the power output falls off badly when modulation occurs and at -4 volts, where the modulation is stronger, the amplitude varies almost equally on both sides of A_n and the current I_0 rises when modulation begins. This is a fairly reliable criterion for high modulation and is a condition to be sought after. The vertical line $A'A$ is drawn through the value of E_c where a further reduction of the latter causes no increase in power output. It would seem that this is the best point for operation as it is near the maximum efficiency at maximum output and about twice as strong modulation is obtained as for -15 volts grid bias. The upper curves of the figure are interesting. It should be noted that at the point where the output becomes constant the output current no longer falls off when modulation begins. At -15 volts bias the output current falls off about 30 per cent and the power more than 50 per cent. Obviously, poor output and modulation result from too great negative bias potentials. Curves A_1 and A_2 show the maximum and minimum amplitudes of the oscillograph beam when rectified modulated high frequency current passes through the element. The percentage modulation was calculated from these values as explained previously. The modulation curve is nearly symmetrical on both sides of the normal deflection at very low values of grid bias, but becomes wholly unsymmetrical on one side at -11 volts. This and larger negative values of E_c produce what is known as "modulating down." Referring again to the lower curves it will be seen that the output is low, the maximum being 150 watts. The output of the amplifier was increased to 400 watts maximum, which again occurred at about $A'A$, and the dotted curves K and M show the results. Curve K shows the input-output efficiency, and M the percentage modulation obtained. This quantity seemed even better for heavy load than for light load. The amplitude curves and other data discussed were obtained with the lower output because of the intense heating of the tubes at the higher output. Figure 17 shows results that are typical for many tubes tried, and for the Hartley master oscillator. Space does not permit giving extra data to prove these interesting results. These quantitative data seem to provide fairly conclusive evidence that a power amplifier system can be made quite efficient and comparable to the constant current system for performance. Figure 18 shows input-output characteristics for the 500-watt amplifier (of Fig. 17) at two grid bias potentials (-3 and -10 volts), representing good and poor modulation. The test of variation of modulation with grid bias potential was repeated for heavier load on the power amplifier and the results checked with those previously obtained. For reduced output the current relation is more nearly linear, see Fig. 18.

It was found that the best value of grid bias is not only low but also quite critical and changes from time to time. In actual use it would

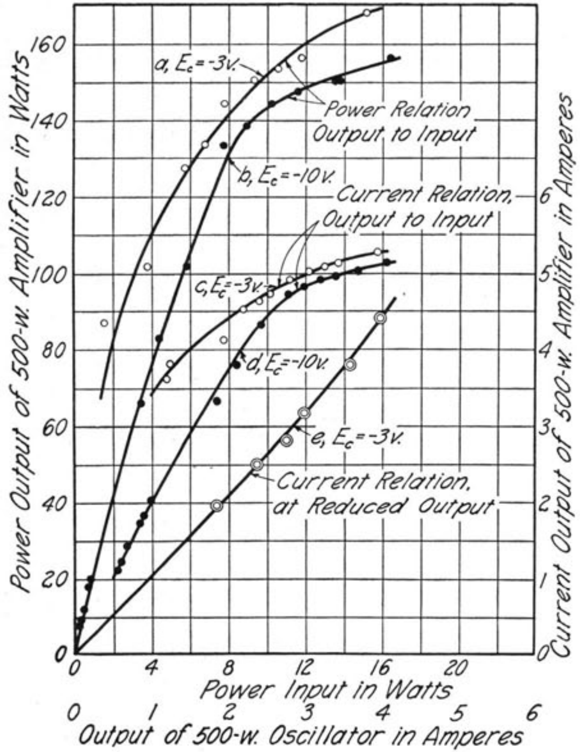


FIG. 18. RELATION OF OUTPUT CURRENT TO INPUT CURRENT IN POWER AMPLIFIERS

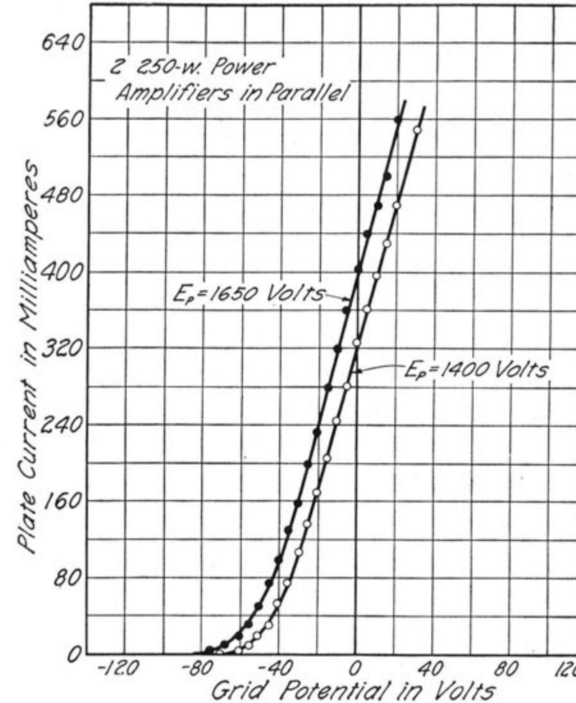


FIG. 19. STATIC CHARACTERISTICS OF TWO 250-WATT POWER AMPLIFIER TUBES IN PARALLEL

have to be varied occasionally so as to keep I_0 from falling off. Figure 19 shows static characteristic curves obtained for the two 250-watt tubes, connected in parallel, which were used in the 500-watt amplifier just studied. These curves probably represent the dynamic characteristics also, because the plate voltage supply was connected directly to the plates of the oscillator except for the radio frequency choke, and the drop through this is small. These curves show clearly why the grid bias must be low and also why it is rather critical. A change in filament temperature changes these curves greatly which accounts for the critical optimum value of grid bias for good results. When working with these systems and using low grid bias, the master oscillator must always be started before turning on the power amplifier. If this is not done the plate current of the latter will increase to an unsafe value. On the whole the results obtained seemed excellent. This is indicated by three things: fair efficiency for a power amplifier tube, 50 per cent modulation or better, and excellent quality when the grid bias was properly adjusted.

22. *Input-Output Characteristics of Power Amplifiers.*—Actual data on the relation between output and input of exciter high frequency power may throw some light on the question of distortion due to a power amplifier. Suppose a power amplifier be excited by a constant current modulated master oscillator. The ability of the power amplifier to give distortionless amplification will depend, partially at least, upon whether or not the current in the output circuit of the amplifier will have a straight line relation to the current in the output circuit of the master oscillator.* Data were obtained for the case of one- and two-stage power amplifiers by varying the plate voltage supply to the master oscillator for a power amplifier system utilizing a 5-watt master oscillator, a 50-watt power amplifier and a 500-watt power amplifier. Figure 20 shows curves plotted between the power output of the three tube circuits. The results were plotted in watts output rather than in amperes output because the tubes are power converting devices. The relation between currents will be linear. The relation seems to be almost linear up to a certain limit beyond which it changes. On the same curve sheet is shown the tube efficiency of the 500-watt amplifier.

A 500-watt power amplifier was then excited by a 50-watt master oscillator, as shown in Fig. 15, and the plate voltage on the latter varied. The results are shown in Fig. 21. The relation between the plate voltage

*It has been shown that in the constant current system this current bears nearly a straight line relation to the modulating potentials.

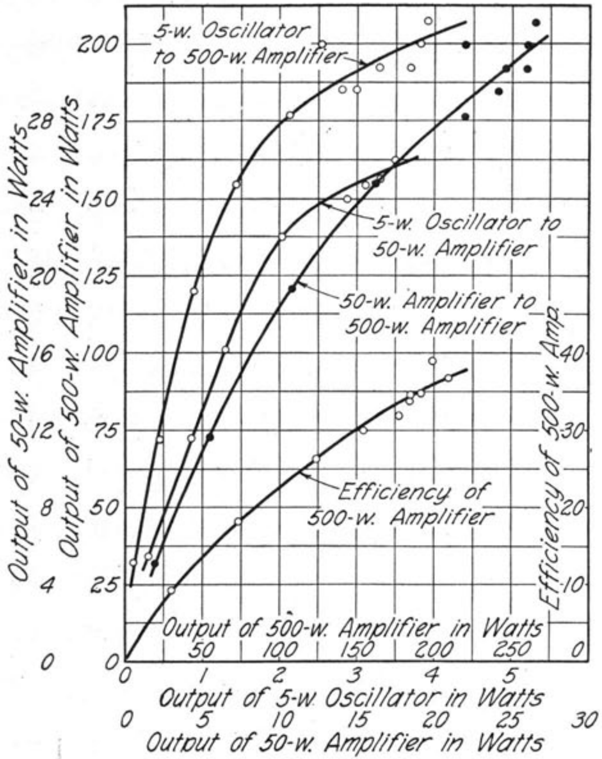


FIG. 20. OUTPUT-EFFICIENCY CHARACTERISTICS IN POWER AMPLIFIER SYSTEM

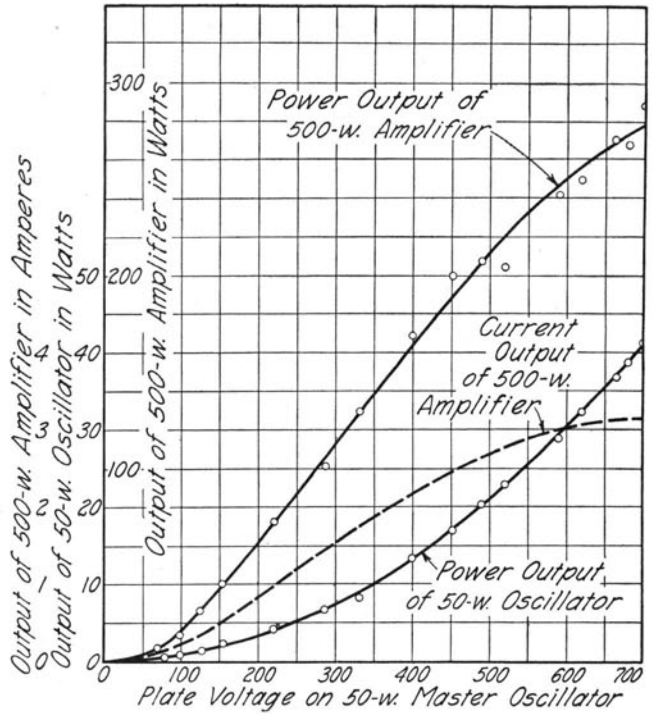


FIG. 21. RELATION OF OUTPUT TO PLATE VOLTAGE IN POWER AMPLIFIER SYSTEM

on the 50-watt tube and its output current is practically linear (square root of ordinates of curve 1). The relation between the output of the 500-watt amplifier and the plate voltage (curve 2) is linear, indicating a source of distortion of the modulated output current and power. The relation between the output current and supply voltage will be about as indicated by the dotted curve. The tube efficiency of the 500-watt amplifier increased uniformly with the output. For 245-watts output the efficiency reached 45 per cent.

Several additional sets of data were taken but results were not plotted owing to lack of space. Results similar to those described for two 250-watt amplifier tubes were obtained for four 240-watt tubes in parallel excited by two 50-watt master oscillators in parallel.

23. *General Conclusions Regarding Modulating Amplifiers.*—It appears from the curves showing the relation between outputs between stages of the amplifier and the master oscillator that the distortion due to this cause is not serious, particularly when the grid potential is properly adjusted, and capable of being varied continuously during operation. This latter provision would also be necessary to obtain effective modulation and good efficiency, as indicated by the tests previously described.

The broader wave usually obtained by users of this system in the past is probably due to one or all of the following causes:

(a) Close inductive coupling of the output circuit to a large coil in the grid of the power amplifier. The frequency fluctuates under certain conditions in such a combination.

(b) The output circuits tuned to slightly different frequencies and tendency for the amplifier to oscillate at certain grid potentials when there is too much inductance in the grid circuit.

(c) Harmonics produced due to wrong values of by-pass condensers and chokes, and to overload or over-excitation of the grid.

VII. Miscellaneous Systems

24. *Grid Leak Method of Modulation.*—The grid leak method of modulation has been in use to a certain extent in other countries,* but is practically out of use in America. In the paper by Culver an oscillogram of grid current and rectified antenna current during modulation is shown, and it appears that the output is modulated not more

*Culver, Proc. I. R. E., Vol. II, No. 5, Oct., 1923, pp. 479-492.

than 10 per cent. Culver states that "deep" modulation is obtained, but does not give quantitative values. A considerable amount of work was done on this system and many quantitative measurements of modulation were made in order to compare it with the others. Owing to the fact that this system is out of use, the oscillograms and curves are not submitted in this bulletin; however, the results will be summarized.

In the case of grid leak modulation the plate to filament resistance of a vacuum tube is used as the variable grid leak resistance of an oscillator tube whose output is impressed on the antenna. The resistance of the "grid leak tube" is varied at speech frequencies by impressing such potentials upon its grid-filament circuit. Culver described transmitters in which the oscillator was a 50- or 100- watt tube and the grid leak was a DeForest "Singer" 20-watt tube. The authors experimented with various tubes and circuits and obtained the best results with a 5-watt oscillator in a Hartley circuit and a "Singer" tube as a grid leak. The filament of the grid leak tube must be connected to the grid of the oscillator and the grid leak tube and its circuits must be well insulated. A characteristic curve of a 50-watt oscillator was obtained and showed that the variation of output with grid resistance was approximately linear only between 3000 and 25 000 ohms, and that the decrease of antenna current with increasing grid leak resistance was nearly exponential. If the plate circuit resistance could be varied between 2000 and 40 000 ohms about 50 per cent modulation could be obtained, assuming 20 000 ohms during no modulation. Such a wide variation in plate resistance of an amplifier tube is difficult to obtain. The percentage modulation tests verified this. A test was then made by varying the grid voltage of an actual vacuum tube grid leak in Hartley and Colpitts oscillator circuits and noting the variation of the output current. The curves obtained were very similar in form and slope to that of Fig. 5 for the case of direct modulation on the grid of a low power oscillator. Variable bias potentials on the leak tube and variable radio frequency chokes were used, but the decrease in output with positive increase in grid bias could not be overcome. There was a limit in negative grid bias (-30 to -50 volts) beyond which the oscillators would not function.

The degree of modulation obtained was observed on the oscillograph screen for many varying conditions, and without exception was very low when the oscillator tube was delivering full power. Fairly strong or "deep" modulation was obtained when the output was very low, about 10 to 20 watts from a 50-watt tube. For full output the modulation was not over 15 per cent at the greatest. If the grid bias of the leak tube is made more than about 30 volts negative the oscillator functions intermittently during modulation, resulting in severe distortion. Without exception the quality improves as the bias of the leak tube is made more positive but the degree of modulation becomes weaker. Using a low output oscillator and several stages of radio frequency power amplification a high degree of modulation and fair quality could be realized; however, another serious defect would be encountered in the falling off of power when modulation obtains. This defect is similar to that noted for the absorption loop method and no adjustment could be made to eliminate it. The decrease is most severe at light load. The oscillograph beam showed the power falling off 60 per cent at low output when modulation occurred. The per cent modulation appears to be about 80 for the very low power output.

An attempt was made to obtain more power, better quality, and less falling off of the power by using two 5-watt Radiotron tubes in parallel as the grid leak with 25 volts positive grid bias. A little improvement was noted but the power decreased 50 per cent when modulation began, and the degree of modulation did not exceed 25 per cent. The quality was observed by listening with a tuned receiver.

The Colpitts type oscillator was used in this test because that was the type employed by Culver. A considerable amount of additional data was taken in an effort to get results more in accordance with the claims of this author, but without success. A Hartley type oscillator gave similar results. Many additional attempts were made to increase the modulation of the 50-watt oscillators, but without success. It is difficult to understand how "deep" modulation was obtained on medium power tubes as claimed in Culver's paper. The oscillogram shown indicated a weak degree of modulation, and failed to show to what degree the radiation current fell off when modulation began. The good results claimed may be possible, but the technique is difficult to attain, and for this reason and in view of the results actually obtained, the grid leak system is not to be compared with some of the other systems investigated in the laboratory.

25. *The Push-Pull System.*—The so-called "push-pull" oscillator is somewhat similar in form to the well-known "push-pull" amplifier, the excitation of the grids being 180 degrees out of phase, and obtained by means of a mid-tapped tickler coil whose ends are attached to the respective grids. The result is that the total excitation of the oscillating circuit must be twice what it would be were one tube removed. It is

claimed by various users that this circuit is a highly efficient oscillator and is *sensitive to grid modulation.* Using two 50-watt oscillators in the circuit the per cent modulation was measured on the oscillograph screen when modulating directly by means of a one-stage (5-watt tube) speech amplifier. About 25 per cent modulation was observed but the power decreased from 65 to 25 watts when modulation began. The secondary of the speech transformer adds too much resistance to the grid circuit of the oscillator, and as this type of oscillator functions best with no added grid resistance, a 0.002 microfarad condenser was shunted around the secondary to by-pass the radio frequency grid current to obtain greater output, but the capacity shunted secondary resulted in weaker modulation. The output could easily be adjusted to 100 watts (normal for the tubes) with no added grid resistance. As in the case of the grid leak system, the quality improves as the grid bias of the leak tube is made more positive but the modulation becomes weaker.

Constant current modulation was tried out for the push-pull oscillator by providing three 50-watt modulator tubes, a constant current choke and a two-stage speech amplifier. The average modulation obtained was about 30 per cent, the output remaining constant when modulation set in. The quality of reception was greatly improved. The efficiency was not as good as for the parallel-connected oscillator system. The relation between the plate voltage supply and the output current was plotted and seemed to be fairly linear between 240 and 1000 volts (normal plate voltage).

The push-pull circuit used in the laboratory called for low resistance in the grid circuits as high resistance resulted in inefficiency. However, oscillograph measurements showed this type of oscillator tube to be more sensitive to grid modulation than the single- or parallel-connected oscillators. It is not possible to obtain as much from a single tube oscillator which, as was pointed out, is insensitive to grid modulation. When using the grid leak method of modulation almost as good results can be obtained with the ordinary single tube oscillator as with the more complicated push-pull type. The quality of reception was unsatisfactory, the distortion was quite severe. Loud sounds caused the tubes to cease oscillating momentarily, due to the high negative grid potentials and resulting high resistance of the grid leak. The grid leak method of modulation was tested on this oscillator because it was in use for some time at one of the larger broadcasting stations in this country. It was later abandoned on account of complaints of the poor quality of modulation. No particular advantage could be found in this type of oscillator using constant current modulation although it had an advantage in short wave transmitting. It may be that if the oscillator is of the persistent type, the relation between the output current and the plate voltage supplied may not always be a direct one.

26. *The Constant Potential System.*—The so-called constant potential system was described by R. A. Heising in his paper on radio telephone modulation to which reference has already been made. He showed two power tubes in series, one functioning as a power amplifier and the other as a variable resistance in series with the power amplifier supply circuit and the plate circuit of the latter. This system was tested for modulation and efficiency with the modification that the power tube was made a self-excited oscillator. The plate voltage supply is double the rated plate voltage for each tube or group of tubes in series, and grids of the modulator tubes are given a negative bias; thus when speech impinges on the microphone the grid potential fluctuates about the normal negative value, and varies the resistance in series with the plate circuit supply of the oscillator. This is essentially a variable current system and hence the supply current must vary, so that filter chokes in the generator leads are detrimental. A very large capacity condenser must be connected across the generator leads to absorb the commutator ripple. If one modulator tube is used it will over-heat; hence, two 50-watt modulators in parallel were used with one 50-watt oscillator in the tests made with this system. The grid bias of the modulators was set at -22 volts. A one-stage speech amplifier (5-watt tube) was used and 50 per cent modulation easily obtained on a sustained "ah" sound. The oscillograph showed the modulation to be symmetrical on both sides of the unmodulated amplitude so that the radiation increased about 23 per cent. The normal output was 50 watts. Decreasing the negative grid bias of the modulators to -8.5 volts increased the output to 68 watts but decreased the degree of modulation about 15 per cent. This test was made with oxide-coated filament 50-watt tubes. When using 50-watt tungsten filament tubes the negative grid bias of the oscillators had to be increased to 60 volts for best results. Increased negative grid bias resulted in one-sided modulation upwards, or a considerable increase in output when modulation began. The efficiency of these systems was measured and was about 25 per cent, disregarding filament power.

Characteristic curves show that the relation between grid potential on the modulators and output current is approximately linear for a wide range of the former. Increasing the power of the speech amplifier beyond a certain limit causes excessive potentials resulting in spark-over in the insulation of the modulator tube sockets. This limits the degree of modulation obtainable unless more modulators are provided.

The quality of reception was excellent when the grid potential was adjusted for the strongest modulation, and the operation of this system seems fairly satisfactory. It has the advantage that it is a little cheaper to operate when using fairly low power tubes, not over 500 watts. No high inductance choke is required, and all that is necessary is a linear relation between speech potentials and output, the operating characteristic curve seems to indicate that the relation is approximately linear.

There are some serious disadvantages in the system. The plate voltage supply must be at least 50 or 60 per cent greater than the rated voltage of the tubes because of the series connection of the plate impedances of oscillator and modulators. Separate sources of filament current supply insulated from each other must be provided. This would be a serious drawback in the case of the high voltage high power tubes. A source of very smooth d-c. potential is needed, with a large capacity across its terminals. The efficiency represented by high frequency power output divided by input from the d-c. supply is low due to the power dissipated on the modulator plates when no modulation takes place. In the constant current system this is eliminated by increasing the negative grid bias until the unmodulated modulator plate current is very low, but it is not possible to do this with the constant potential system on account of the accompanying reduction in power output. Modulation is limited to 50 per cent due to destructive potentials created in the modulator sockets.

VIII. Modified Theory of Distortion

27. *Inherent Distortion—Constant Current Modulation.*—The commonly used triode detector obeys what is known as the "square law" and in general the anode current, i_a, is given by Appelton* to be

$$i_a = a_0 + a_1 v + a_2 v^2 + a_3 v^3 + \qquad (1)$$

where v is the instantaneous voltage impressed on the grid.

Taking
$$v = I_0 \sin \omega t + K I_0 \sin \omega t \cos pt \qquad (2)$$

for the conventional modulated wave (see page 6), the second term produces only amplification; hence, rectification occurs largely from the third term $a_2 v^2$.

*Proc. I. R. E. Vol. XII, No. 3, p. 279.

Then $$i_a = a_2^2 (I_0 \sin \omega t + KI_0 \sin \omega t \cos pt)^2$$

$$= a_2^2 \frac{I_0}{2} [1 + \frac{K^2}{2} + \frac{K^2}{2} \cos 2\,pt + 2K \cos pt]$$

$$- \frac{a_2^2\, I_0^2}{2} \sin 2\,\omega t\, [1 + \frac{K^2}{2} + \frac{K^2}{2} \cos 2\,pt + 2K \cos pt] \qquad (3)$$

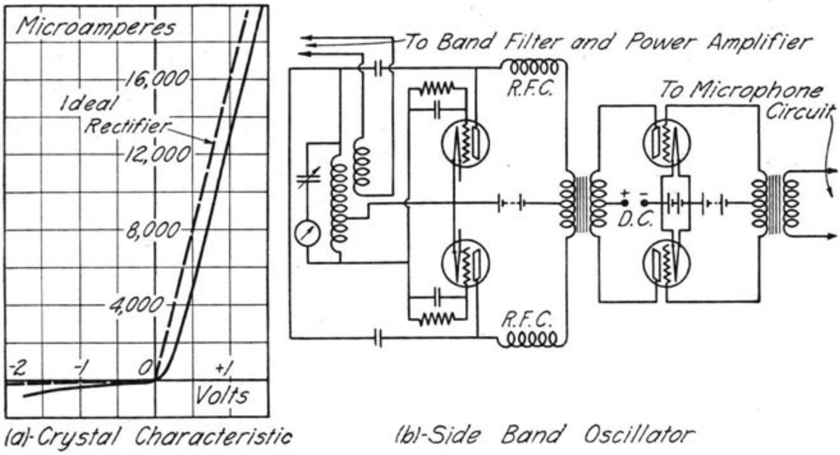
The first portion contains only constant terms and audible frequency terms while the second portion contains only radio frequency terms. Interest lies then in the first portion of equation (3). The signal is accurately reproduced by the term $2K \cos pt$ and $\frac{K^2}{2} \cos 2\,pt$ is a double frequency distortion component. For 100 per cent modulation $K = 1$ and the ratio of signal to distortion is 4 to 1; for 50 per cent modulation $K = \frac{1}{2}$ and the ratio is 8 to 1. With the present type of triode detector 50 per cent seems to be the permissable upper limit for good quality. Hence, in practice, half of the output current is of no use for modulation and this entails a large waste in power and lack of economy of transmission.

More efficient transmission could be accomplished by providing a higher degree of modulation on the loudest sounds, say 80 per cent, and providing an additional $I_0 \sin \omega t$ component at the receiver by means of a separate oscillator, or an autodyne detector. The amplitude and phase of this component can easily be varied for the best results. As a simple case let $K = 1$ and let the local $I_0 \sin \omega t$ be one-half of the corresponding incoming wave component. Then in equation (3)

$$i_a = a_2^2 \frac{I_0^2}{2} (1.5\, I_0 \sin \omega t + 1.5\, I_0 \sin \omega t \cos pt)^2$$

and it is found that the ratio of signal to distortion amplitude is 6 to 1.125 instead of 4 to 1 for the case of 100 per cent modulation without the added so-called "carrier" component.

The triode detector rectifying by means of a "square law" relation is a make-shift. The ideal condition for reception of a deeply modulated wave without distortion could be attained if a perfect linear rectifier were available. Let Fig. 3a represent the modulated high frequency currents. A perfect rectifier would cut off the lower half of the wave as shown and the current through a telephone receiver would follow the wave MN, or, due to the smoothing out action of the circuits might even follow $a'b'$ of Fig. 3b. Both of these conditions would give better



(a)-Crystal Characteristic (b)-Side Band Oscillator

FIG. 22. CRYSTAL CHARACTERISTIC AND SIDE BAND OSCILLATOR

reproduction of the signal wave. Some of the crystal rectifiers actually possess to a close degree this desired characteristic at audio-frequencies. For instance a crystal characteristic like that of Fig. 22 approximates the ideal condition. This curve is for a "Lenzite" crystal and "Cerusite" gives quite similar results. The dotted curve of the figure gives the ideal condition. With such a rectifier the average amplitude of a positive half-wave of radio frequency current of Fig. 3a is given by

$$\frac{1}{\pi}\int_0^{\pi} I_0 \sin \omega t \, d\omega t$$

This is in turn modulated by a pulsating audio-frequency wave $A + A \cos pt$ for a pure tone in which $f_a = \dfrac{p}{2\pi}$. Hence, for the case of a current $I_0 \sin \omega t$ modulated by a complex audio-frequency wave the equation of the curve MN representing the audio-current is

$$i_a = \frac{1}{\pi}\int_0^{\pi} I_0 \sin \omega t \, d\omega t \sum{}_{\theta_1 P_1}^{\theta_N P_N} [A + A \cos (pt + \theta)] \qquad (4)$$

where the range from P_1 to P_N includes the component frequencies and θ_1 to θ_N their corresponding phases. It will be noted that no extraneous audio-frequency term appears in the application of equation (4); hence, the signal is accurately reproduced without distortion. Thus for a pure tone of frequency $\frac{p}{2\pi}$,

$$i_a = \frac{2I_0}{\pi}[A + A\cos(pt + \theta)]$$

Also for 100 per cent modulation $A = I_0$ but no change in the form of equation (4) results; hence, the loudest tones may produce this degree of modulation with an increase of nearly 100 per cent in the distance covered by the transmitted signal. The advantage of providing an efficient radio frequency amplifier and crystal rectifier of the proper characteristic cannot be emphasized too strongly. The radio frequency amplifier is usually necessary to obtain a voltage variation on the crystal sufficiently large to result in a nearly linear characteristic. For the crystal of Fig. 22 the amplitude of the impressed e.m.f. should be one volt or more. If all theoretical conditions are as is assumed in the case of the discussion of the triode rectification, distortion would probably be more objectionable than it really is in practice. The reasons for this are probably many. For instance, Fig. 12 shows that after the modulating potential reaches a certain limit the modulation is no longer linear but probably obeys a square root law or follows the saturation curve, which apparently would partially annul the distorting effect of the square law rectification. Dynamic characteristics of modulator and oscillator tubes also have a modifying effect on assumed conditions.

28. *Non-Continuous Carrier Transmission.*—Recently a method of transmission was developed and tested with considerable success wherein the transmitter radiated power only when sound occurred at the microphone.* This was a non-continuous carrier wave method, and there was thus no carrier wave in the sense that it would always be present. However, what is known as a carrier component existed during sound occurrence. The equation for antenna current is

$$i = (M + M\cos pt)\, I_0 \sin \omega t$$

ω and p have the same meaning as in equation (2). During silence

*"Non-Carrier Radio Telephone Transmission," Univ. of Ill. Eng. Exp. Sta., Bul. No. 145.

$M = 0$ and $i = 0$. The form of this current is similar to that of Fig. 1 or Fig. 3 except that the unmodulated amplitude was, of course, zero or very small. For the triode detector

$i_a = S[(M + M \cos pt)\, I_0 \sin \omega t]^2$ where S is a constant and the audio-frequency component

$$i_{af} = SM^2\left(1 + \frac{1}{2} + \frac{1}{2}\cos 2\,pt + 2\cos pt\right) \tag{5}$$

Comparing this with the constant current modulation system it is seen that the amplitude of the cos pt term is the same as for 100 per cent modulation. It will be noted that the ratio of the signal to distortion component is 4 to 1, and is not dependent on the degree of modulation. As in the constant current system, a gain is made in the ratio by the use of an autodyne receiver. It would seem that distortion might be serious with this type of transmission, but tests showed it to be highly satisfactory. Curves showing the relation between modulating potential and antenna current showed a very marked square-root or saturation characteristic; this probably modified the results greatly and to good advantage. This type of modulation results in a considerable saving, there being no unmodulated radiation, and the absence of interference with local receiving stations is of great importance. Here again an ideal linear rectifier will give perfect reception for

$$i_a = \frac{2\,I_0}{\pi}(M + M\cos pt)$$

where i_a is the audio-frequency current through the telephone. The cos pt modulating wave is accurately reproduced and the modulation is always complete except for the slight radiation that is usually necessary to keep the oscillator tubes excited.

29. *Modified Single Side Band Transmitting Apparatus.*—The authors recently experimented with a side band transmitter of the form shown in Fig. 22b. This is a simpler apparatus than that used by the Western Electric Company* in this type of transmission and is thought to be more easily applied in the case of short waves. The oscillators function on both loops of the alternating voice frequency supply

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*Hartley, Proc. I. R. E., Vol. XI, No. 1, pp. 34-55.

ERRATUM

Equation (6) should read:

$$i_a = I_0 \sin \omega t + \frac{I_0}{2} \sin (\omega + p) t$$

in the receiving antenna.

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waves during the occurrence of sound and produce the side band components only. For

$$i = I_0 \sin \omega t \cos pt$$
$$= \frac{I_0}{2} \sin (\omega + p)t + \frac{I_0}{2} \sin (\omega - p)t$$

It can be shown* that when the lower side band $\frac{I_0}{2} \sin (\omega - p)t$ is removed by means of a suitable band filter the remaining $\frac{I_0}{2} \sin (\omega + p)t$ contains only one-sixth as much power as the conventional 100-per-cent-modulated wave of amplitude I_0. This component can be transmitted and if the receiver has the component $I_0 \sin \omega t$ supplied,

$$i_a = [I_0 \sin \omega t + I_0 \sin (\omega + p)t^2] \qquad (6)$$

From the product term the cos pt component is obtained and the signal is reproduced. Equation (6) reduces to

$$i_a = [I_0 \sin \omega t + \frac{I_0}{2} \sin (\omega + p)t]^2$$

and

$$i_{af} = \frac{K\,I_0^2}{2} \cos pt \qquad (7)$$

It will be noted that the signal is accurately reproduced without distortion even though the square law rectifier is used. Thus the ideal linear rectifier is not needed as in all the other modulation systems discussed. A potential difficulty in using single side band transmission at the shorter broadcast wave-lengths lies in the design of an efficient band filter. The design of a band filter for the higher radio frequencies (750 to 2000 kilocycles) is quite a different problem from that for 25 or 50 kilocycles. The effect of phase shift on distortion has been ably discussed by Hartley in his paper already referred to, and hence was not touched upon. Experimental work on this problem would yield information of paramount importance.

IX. Summary and Conclusions

30. *Summary.*—A complete summary of the results of the work undertaken would require too much space. A very brief résumé of

*Heising, Proc. I. R. E., Vol. IX, No. 4.

the relative merits of the various systems studied is best given in a tabular form as follows:

Type or Name of System	For Connection Diagram and Performance See	Degree of Modulation	Quality of Reception	Efficiency and Economy	Reliability and Ease of Adjustment	Average Desirability
Constant Current	Figs. 7, 8, 9, 10, 11, 12	High	Excellent	Good	Excellent	A
Modulating Amplifier	Figs. 15, 16, 17 18, 20	Medium-High	Fair-Good	Good	Fair-Good	B
Constant Potential		Medium	Good	Fair	Good	C
"Logwood"	Fig. 4.	Poor	Excellent	Poor	Excellent	D
Absorption Loop	Fig. 4	Fair-Good	Good	Poor	Good	D
"Push-Pull" (c. c.)		Medium	Good	Good	Poor	D
Grid Leak		Poor-Fair	Poor	Fair	Poor	E
Grid Leak (Low Power)		Medium	Fair	Fair	Fair	C

It must be remembered that this estimate is based principally on laboratory circuits, and the value of the conclusions may possibly be modified somewhat thereby. At the same time it is quite safe to conclude that a system which shows up poorly in the laboratory could hardly be expected to do well in practice, provided important and necessary precautions have been taken to obtain the best possible results, as was consistently done in all of the work.

In regard to the well-known systems tested it would appear that the constant-current-modulated power amplifier systems and the straight constant-current system, with power tubes for modulators, are by far the most satisfactory for practicability, economy, and high efficiency. In the case of medium power radiophone sets of from 250 to 1000 watts for commercial marine use and military or naval use, the power amplifier modulated by means of a 50- or 100-watt constant-current system is the most practical and economical. Saving is effected in cost of tubes, space, filament power, and cost of constant-current choke capacity.

Suppose a 500-watt radiophone is desired for this use. Two 250-watt power tubes are needed, and if they are used as oscillators three 250-watt modulators are needed, as well as a speech amplifier, expensive choke coil, and 150 per cent additional filament power. If a 50-watt master oscillator is used all of these are dispensed with. Power for both the 50-watt tube and the speech amplifier can be supplied by the same small motor generator or dynamotor. Two 50-watt modulators are also needed but the cost of the three 50-watt tubes is 30 per cent less than the cost of one 250-watt modulator tube.

The oscillograms and data have shown that the percentage modulation obtained by the power amplifier system is comparable with that of the best constant-current equipment, and with proper design and adjustment it may be as good as that of the latter, as usually used in practice. It is very important to provide a continuously variable grid bias potential for the power amplifier tubes with the aid of a potentiometer control. This bias potential should be regulated so that the plate current of the power amplifier tubes is nearly a minimum (see Fig. 17). It appears that this important fact has not been appreciated by those who have tried the modulating amplifier system in practice and have in many cases abandoned it later in favor of the constant-current system. From the standpoint of the fundamental principles of vacuum tube amplifiers there is no reason why audio-frequency modulated radio frequency power cannot be amplified to a high degree, satisfactorily, if conditions are right and important adjustments are carefully made as in the tests described.

For radio broadcasting constant-current modulation has many advantages, most prominent of which are the simplicity of construction and adjustments of both transmitter and receiver. Theoretical considerations discussed show that the linear crystal rectifier improves the quality of reception greatly even with nearly 100 per cent maximum modulation of the wave increasing the efficiency of transmission. A limitation on this is the increased difficulty of obtaining strong modulation in medium and high power transmitters, as shown by the experimental work described. The linear crystal rectifier would also make the reception of non-continuous carrier wave transmission and single and double side band transmission more nearly free of the inherent distortion present when the square-law triode rectifier is employed.

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